Journal of Cleaner Production 236 (2019) 117502

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Defining water-related energy for global comparison, clearer communication, and sharper policy

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ARTICLE INFO

Article history:
Received 17 October 2018
Received in revised form
31 May 2019
Accepted 29 June 2019
Available online 2 July 2019

Handling Editor: Prof. Jiri Jaromir Klemeš

Keywords:
Water-energy nexus
Water supply
Wastewater
Water end use
Energy consumption
Science to policy

ABSTRACT

The need for energy in water provision and use is obvious, however the drivers are often complex, difficult to assess, and often inconsistently presented. Here we build a clearer definition and conceptual framework of "water-related energy". We apply this framework to harmonise data and results across disparate studies so that regional estimates of water-related energy can be compared in a consistent way for the first time. We show how widely different boundaries have been used for analysis including or excluding: water and wastewater utilities, as well as residential, commercial, industrial, and agricultural water users. Consequently, understanding of what constitutes "water-related energy" is widely divergent. We demonstrate how up to 12.6% of total national primary energy use can be influenced by water, when (i) water-related energy of water users, and (ii) energy use by water utilities, are all included. Water heating for residential, commercial, and industrial purposes is the dominant fraction. Water and wastewater utilities use 0.4–2.3% of primary energy or 0.6–6.2% of regional electricity, mostly for water pumping. This is substantial, but lower than frequent claims in the media and reports. To answer how is miscommunication influencing policy? we undertake a novel systematic tracking of communication to demonstrate distortion between research and its application in government reports, media and policy. We show that significant confusion is caused by (i) unclear or inconsistent boundaries (ii) widely differing use of terms for water "system", "sector", and "supply", (iii) frequent failure to distinguish 'energy' from 'electricity' and (iv) wide use of non-standard units. While acknowledging that media is often less accurate than government reports, and that peer-reviewed articles generally have highest overall quality, we observe miscommunication and inconsistency in all publication forms. We argue a global protocol is needed to improve consistency of analysis and sharpen policy towards sustainable water end use because this is where most water-related energy occurs. We establish a foundational framework and definitions for this protocol while recognising much more needs to be done. The strong practical and theoretical implications of the work for sustainable cleaner production are elucidated. This is timely, as global quantification of water-related energy has yet to occur particularly for water end-use which is the dominant component.

1. Introduction

Increases in greenhouse gas emissions from energy use associated with the provision and use of water is a significant issue

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https://doi.org/10.1016/j.jclepro.2019.06.333
0959-6526/© 2019 Published by Elsevier Ltd.

(Rothausen and Conway, 2011). Energy and water are inextricably linked resources and indispensable inputs to modern economic and national security (Hightower and Pierce, 2009). Understanding the water-energy nexus may help minimise energy and water consumption and reduce environmental emissions (Wakeel et al., 2016). Understanding "water-related energy" (See Section 2.1 for definition) as a sub-component of the wider nexus is a promising step in this wider aim.

A wide range of regional, national and global estimates of water-related energy use have been published. Systematic recent analysis indicates that water supply and wastewater treatment accounted for 1.7%–2.7% of total global primary energy use in 2010 (Liu et al., 2016). However, a much larger pool of energy is affected by water when end use of water is also considered. For example, in the United States, 12.6% of national primary energy consumption is accounted to the use of water, primarily for heating, as well as the supply of water and disposal of wastewater (Sanders and Webber, 2012).

Despite water heating standing out as the most significant water-related energy use activity (Rothausen and Conway, 2011), most literature on "water-related energy" focuses on "utilities" (Kenway et al., 2011). Many studies address pumping and treatment of water and wastewater because energy consumption by utilities represents a significant fraction of operational cost (Badruzzaman et al., 2015; Conrad et al., 2011; U.S. Environmental Protection Agency, 2013). The US Congressional Research Service notes "energy is the second-highest budget item for municipal drinking water and wastewater facilities, after labor costs" (Copeland and Carter, 2017). Electricity represents well over 10% of total operating cost at water and wastewater utilities, with a significant number of utilities having energy costs that exceed 30 percent in the US (Tarallo et al., 2015).

Water-related energy has been quantified in several studies. However, the authors here are concerned by repeated and regular misunderstandings, misinterpretations and miscommunications of water-related energy use in some government reports and policies, as well as international presentations and media statements. We provide examples and analysis for California in Section 3.3.

1.1. Objectives, scope and contribution of this article

Given that water-related energy is substantial and there are signs that it has been inconsistently communicated, our objectives were to (i) develop a more consistent framework for conceptualising and assessing "water-related energy", (ii) apply this framework to existing studies and datasets to enable comparisons, and (iii) track how water-related energy has been communicated. Specifically, this was intended to address this gap by answering the research questions including: *How significant is water-related energy when water "users" and "utilities" are included? How are miscommunication, misinterpretation and misunderstanding of water-related energy influencing policy? And, How will clearer assessment and communication of water-related energy shift discussion?* All three questions are inter-related.

Our overarching aim was to bring to light the systematic and widespread miscommunication of an issue which we perceive to be at the core improved management of the water-energy nexus. Our aim necessitated that we define key terms, inclusions, boundaries, and transformations. It also required that we then use the framework consistently to analyse global data and studies in order to quantify the energy impact of water. We did this for both (a) end use of water in the residential, industrial, commercial and agricultural sectors and (b) by water utilities who provide water and wastewater services.

By providing more standardised definitions of "water-related energy", we sought to increase the value of existing and future publications by enabling comparisons of their results without the need for significant recalculations to account for different interpretations. The inability to compare results across studies is a major shortcoming in the energy-water nexus literature to date. We then systematically tracked the accuracy of water-related energy communications in academic studies and media but, more importantly, in government reports and policy. After documenting significant confusion and distortion through communication, we recommend steps for improved analysis, definitions, development of global protocol, and policy.

2. Materials and methods

This study involved three key steps each tied to one of the research objectives (further details are provided in Supplementary Information 1 and 2):

- Step one defined water-related energy and other associated terminology (Section 2.1). Definitions were built on common usage of terms in industry and the literature, giving consideration to the setting of clear category boundaries.
- Step two applied these definitions to review, harmonise and analyse studies and datasets that quantified water-related energy (Section 2.2). We compiled and consistently analysed studies and datasets of (a) urban water impact on primary energy consumed by end-user and (b) water utility energy use. The results were presented as both absolute quantity and a fraction of regional/national total primary energy use. Our analysis of global studies was a necessary step in establishing as accurately as possible, the current global significance and components of water-related energy.
- Finally, Step three analysed examples of water-related energy communication in the literature (Section 2.3). The above definitions and data analysis were necessary steps before we could identify illustrative examples of communication pitfalls and track their impact on later studies, grey literature and policy. In order to improve clarity we also developed definitions of "misinterpretation", "misunderstanding" and "miscommunication" (Section 2.1). We used these definitions and a source-tracking register, to identify progressive distortion in messages in published literature.

The novelty of the method includes i) the development of a clearer conceptual framework of water-related energy, ii) the application of the framework to compile and compare water-related energy quantified from different studies and datasets, and iii) the development of a first global source-tracking register to track communication of water-related energy.

2.1. Definitions

For this study, and as a suggested cornerstone of the framework, the following definitions were developed and used:

- *Water-related energy*: energy use by (i) water and wastewater utilities and (ii) water users, where that energy use is affected by water use, heating, pumping or treatment. More generally, it is the energy consumed to change water's location or its physical, chemical, thermal or biological properties. In this definition, energy use is "water-related" if changes in water use, pumping or treatment lead to changes in energy consumption in a cause-and-effect relationship. We recognise that in some studies "water-related energy" could also include energy "embedded" in the provision of goods and services, for example, energy needed to make chemicals, concrete and steel (Corominas et al., 2013). However, "embedded energy" should be specifically included in the definition by authors when it is relevant.

- *Water sector*: those "responsible for providing sustainable, secure and safe raw water, drinking water and wastewater services. These services include water harvesting; water manufacturing (e.g. desalination); storage; treatment and distribution; and wastewater removal and treatment. At times urban water utilities are also responsible for stormwater and flood mitigation services. Urban water services are generally provided by state and territory -government owned entities or by local councils." (Australian Government Productivity Commission, 2011). This definition is consistent with economic or industrial sector definitions. Standard classifications of industrial sectors provide clear guidance indicating a sector should only include those providing a service for others.
  The water sector includes entities involved in (i) planning, procuring and supplying water to households, commercial, industrial and agricultural users, (ii) collecting, treating and disposing or recycling wastewater (sewage and trade-waste), and (iii) managing drainage and stormwater for flood mitigation, environmental protection, disposal or recycling purposes (Australian Government Productivity Commission, 2011). Water users (e.g. residential, industrial, commercial and agricultural consumers) should not be included in the term "water sector". This is because they would arguably also form part of the "energy sector" and "agricultural sector", among others. Such an approach would lead to double accounting in a multi-sector study.
- *Water cycle*: the engineered water cycle, or the movement of water by humans from its collection in catchments, through its use and its return to the environment after treatment (Melbourne Water, 2017). This is distinct to the natural hydrological water cycle that includes evaporation, condensation, precipitation, infiltration, run-off, and transpiration.
- *Water system*: typically, a series of interconnected "physical" or infrastructure systems for managing water supply, sewerage and stormwater drainage. "Water systems" refer to infrastructure providing water, wastewater, and/or stormwater services as well as self-supplied and on-site services. Traditionally, the term "water system" refers to the infrastructure (pipes, pumps and treatment facilities) for supplying water services. Definitions vary, such that different infrastructure components and parts of the water cycle may be included or excluded. Often these definitions are not clear, or repeatedly shift, even within a given article (Wakeel et al., 2016).
- *Water utilities:* the formally regulated institutions that provide water (generally potable) to customers, excluding self-supplied water (i.e., industries or farms that have a legal water right to pump water directly from its source). "Utility" energy use is typically dominated by use of grid-electricity for pumping and treating water and wastewater (Table 1) but use of natural gas, diesel, and renewable energy sources (e.g. combustion of methane from anaerobic digestion of wastewater, and/or solar photovoltaic, hydropower and wind energy) can be substantial in some water systems.
- *Water users:* actors in residential, industrial, commercial, agricultural and other sectors that withdraw and/or consume water from a utility or directly from a source (i.e. self-supply). For residential water users, connections of water and energy include water heating for showering, bathing, clothes-washing and taps. In industry and commerce, "water-related energy" can include for example steam production, air-conditioning and cooking.
- *Misinterpretation*: communication error that occurs when a statistic has been applied incorrectly or out of context.
- *Misunderstanding*: communication error that involves incorrectly estimating or calculating values, including using overly generalised assumptions, or misapplying energy conversion factors.
- *Miscommunication*: communication error resulting from imprecise language leaving significant opportunity for misunderstanding or misinterpretation.

2.2. Review and analysis of data and comparison of regions

We conducted a review of studies and datasets that quantified water-related energy at utilities and/or water users in different regions and countries (Table 2). We then applied the proposed framework of standardised terminology and boundary definitions (outlined in Section 2.1) to these studies. Table S1-1 of Supplementary Information 1 shows the derived results from these studies and datasets. Where necessary, additional data were used to calculate components of water-related energy to enable comparison across studies. (Examples of this include the fraction of domestic water heating by fuel source, and primary energy conversion factors).

Full details are contained in Supplementary Information 1, the key components of which include:

i. Water-related energy as a percentage of total primary energy consumption by region (Table S1-1, Figure S1-1).

Table 1
Utility and water-user examples of water-related energy and typical forms of energy.

Water Cycle Element	Examples	Typical energy forms used			
		Secondary energy[+]	Primary energy		
		Grid electricity	Natural Gas	Diesel	Renewables
Utilities[a](water)	Pumping - Raw and distributed water.	✓	✓	✓	✓
	Treatment – Reverse osmosis, filtration, air stripping, chemical feed.	✓		✓	✓
Water users (consumers, end-users)	Residential[#] water heating for showering, clothes washing, dish washing, taps, spas, kettles.	✓	✓		✓
	Industrial water heating, steam production, chilling, air conditioning.	✓	✓	✓	✓
	Commercial water heating, cooling, ice making, cooking.	✓	✓	✓	✓
	Agricultural pumping and booster pumping.	✓		✓	✓
Utilities[a] (wastewater)	Pumping sewage and treated wastewater.	✓		✓	✓
	Treatment. Aeration, anaerobic digestor heating, odour control, screening.	✓	✓	✓	✓

[a] The term "water sector" is often used to describe all water and wastewater utilities together. [#]Often referred to as "households or community". [+]Includes electricity generated from coal, nuclear, gas and other primary energy sources as well as grid-renewables.

Table 2
List of reviewed studies and datasets.

Region of study	Reference year	Data sources
European Union	2012	Enerdata (2017)
Global	2010	Liu et al. (2016)
Australia	2015	Department of Industry (2015)
Brazil	2012	Nogueira Vilanova and Perrella Balestieri (2015)
Canada	2013	Natural Resources Canada (2013)
China	2011	Li et al. (2016)
Japan	2006	Japan Water Research Center (2013); Kondo (2009); Minister of Land (Undated)
Netherlands	2007	Gerbens-Leenes (2016)
Singapore	2012	Vincent et al. (2014)
Spain	2008	Hardy et al. (2012)
United States	2010	Sanders and Webber (2012)
Australia - urban	2007	Kenway et al. (2008)
California	2001	Klein et al. (2005)
South East Queensland	2012	Kenway et al. (2015)

ii. Utility electricity consumption as a percentage of total regional electricity consumption (Table S1-2, Figure S1-2).
iii. Basis for quantifying water-related energy for each region (Table S1-3).
iv. Agricultural water supply and on-farm pumping inclusions in electricity consumption by water and wastewater utilities (Table S1-4).
v. Primary energy conversion factor by region and year (Table S1-5).

Most of the reviewed studies and datasets reported water-related energy in final energy consumption units from electricity and/or natural gas use. Only a few reported water-related energy in primary energy consumption units. The electricity use within the final energy consumption ($E_{final,\ electricity}$) does not account for energy losses in conversion and transmission. For a consistent comparison of water-related energy across all the studies and datasets, regional-specific primary energy conversion factors (CF) were applied to convert reported electricity use values that are in final energy consumption units to primary energy consumption units. All non-electricity final energy consumption ($E_{final,\ non-electricity}$) was assumed to be equivalent to primary energy (i.e., their conversion and transmission losses are not considered). Consequently, primary energy consumption is defined as:

$$E_{primary} = CF \times E_{final,\ electricity} + E_{final,\ non-electricity}$$

The conversion factor is the ratio of primary energy consumption in the electricity generation sector to total final electricity consumption in all other sectors. The regional-specific factor was derived from the International Energy Agency's energy balance of individual country/region for the corresponding year. Table S1-3 details the basis for quantifying water-related primary energy consumption from individual studies or datasets, with the list of factors provided in Table S1-5 of Supplementary Information 1.

2.3. Analysis of communication of water-related energy literature

The review of policy-related miscommunications began with the development of categories of common miscommunications and then identification of literature and related communication issues/challenges. Because our purpose was to discuss how the misuse of these statistics could influence policy- and decision-makers, we focused largely on examples from non-academic literature to illustrate the problem and how it can be propagated. By necessity this meant we also had to review key academic publications to establish the original statements on water-related energy. Publications reviewed were identified in three ways:

1. We identified recent water-energy related legislation that targeted water utility operations and tracked the documentation behind and media releases surrounding that legislation.
2. We identified the publications in an ad hoc manner, i.e., in the course of related research.
3. We determined statistics that were frequently misused in the prior two steps and used internet search engines to see how they were being used in media (e.g., searching for "California 20% water energy").

Academic studies included in the literature analysis were generally identified in an ad hoc manner and do lead to some geographic bias in the examples (e.g., California is potentially over-represented because the drought has fostered several recent policy initiatives covered in the media). However, even without an exhaustive, worldwide search, the prevalence and potential negative policy implications of water-related energy miscommunications are clear. The literature evaluated in the miscommunication analysis is summarised in Table S2-1. Publications are listed in chronological order. References without a precise publication date are in approximately the correct order. The table includes the relevant quoted text, the citation information for any related references, the type of error, and our assessment of the potential policy suggestions explicitly or implicitly made in the publication.

3. Results and discussion

3.1. How significant is water-related energy when water "users" and "utilities" are included?

Our analysis of studies, and comparison of water-related (primary) energy use by utilities and water users in countries or regions is presented in Fig. 1. This has two main categories: (i) water and wastewater utilities and (ii) water users. Water and wastewater utilities covers the use of energy for treating and conveying water to all users. Water users includes energy related to water use in residential, industrial, commercial and agricultural sectors. This includes heating of water in residential, commercial and industrial sectors, and on-farm agricultural water pumping. Water and wastewater utilities typically use between 0.4% and 2.3% of total primary energy use depending on inclusions. Water-related energy of water users comprised 2.6%–12.1% of regional primary energy when all users are included (i.e., residential, commercial, industrial and agricultural water users). Water-related energy by water users accounted for approximately 24 times the energy that utilities use in the United States. In another example, residential water heating

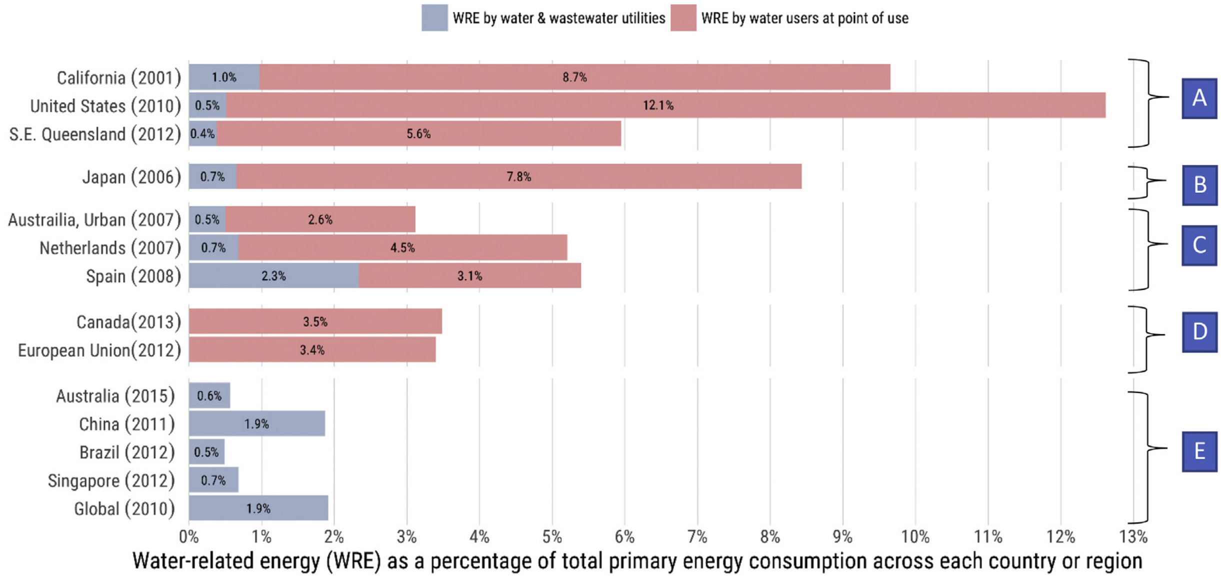

Fig. 1. Water-related energy as a percentage of total annual primary energy consumption in each country or region. Group A-Include water-related energy in residential, industrial, commercial and (other than the S. E. Queensland study), agriculture, Group B – Include residential and commercial water heating, Group C- Includes residential water heating only, Group D – Includes only residential water heating (and excludes utilities), Group E – Includes only utility energy use. (See Table S1-1 and Table S1-3 in the Supplementary Information 1 for references).

alone in Spain accounted for over 1.4 times the energy of utilities there.

Quantifying electricity consumption by utilities as a percentage of regional or national use (Fig. 2, Table 1) indicates that utilities consume from 0.6 to a maximum of 6.2% of total annual regional (or national) electricity consumption. This is significantly less than the 10–20% claimed by many articles (See also Table S2-1). We note that electricity use (and energy use generally) by utilities is highly dependent on many local conditions including distance, elevation and quality of raw water sources for water, and the degree of treatment and pumping for wastewater.

3.2. Global and national misinterpretation, misunderstanding, and miscommunication

Our review identified a range of publications that have misinterpreted, misunderstood, and/or miscommunicated “water-related energy” (see Table S2-1 for complete analysis). A summary is provided in Fig. 3 with an example thread of global studies in Table 3. A number of important and influential global water-energy estimates have overemphasised or wrongly attributed most energy to water treatment and pumping. For example, in 2012, the United Nations claimed “Out of all energy produced globally, 7%–8% is used to lift groundwater and pump it through pipes, and to treat both groundwater and wastewater (Hoffman, 2011) - a figure that rises to around 40% in developed countries (World Economic Forum, 2011)” (UNESCO, 2012). More recent detailed analysis has shown these numbers to be significant overestimates. Global primary energy use for all water pumping from groundwater and other sources, treatment and delivery was 1.7–2.7% of global primary energy use in 2010 (Liu et al., 2016). The 7%–8% claim was based on two broad assumptions. Firstly, that 1,000 cubic miles of

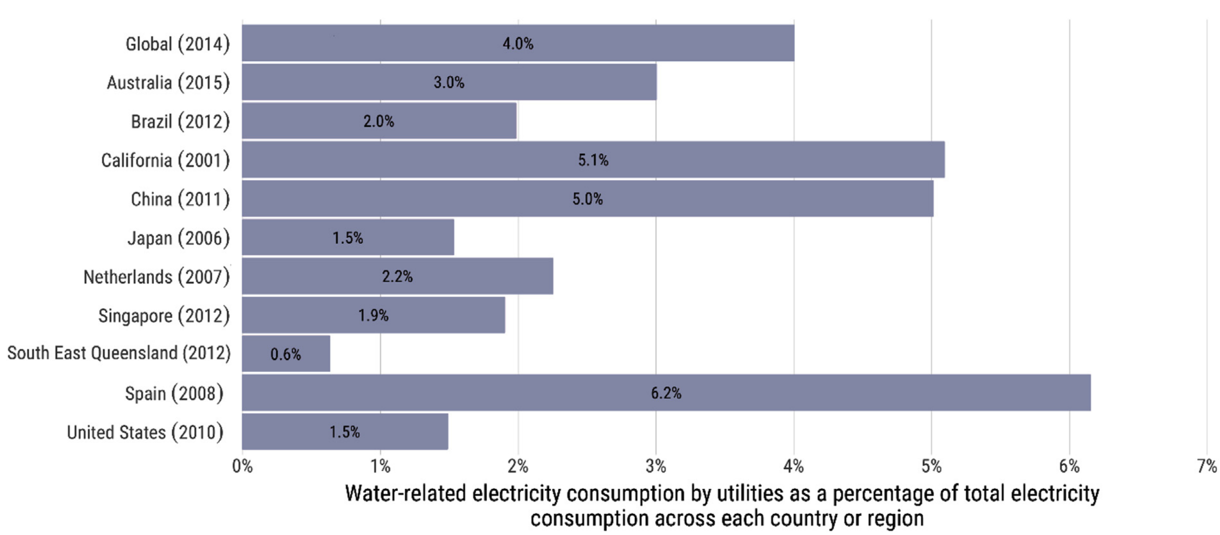

Fig. 2. Electricity consumption by utilities as a percentage of total electricity consumption across countries and regions. (See Table S1-1 and Table S1-3 in the Supplementary Information 1 for references).

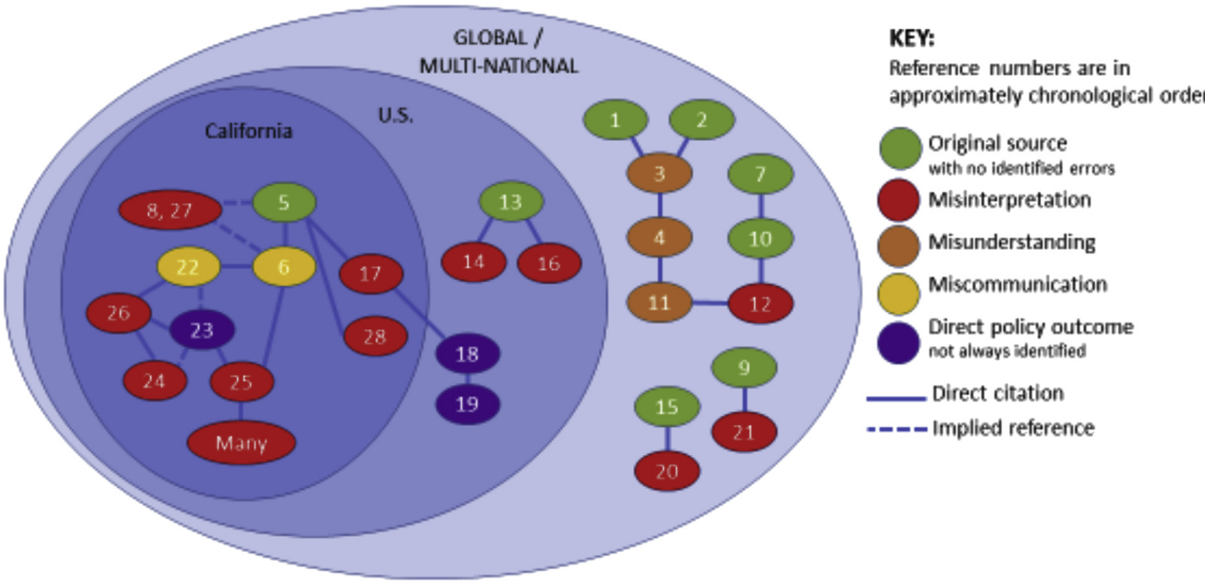

Fig. 3. Summary of the propagation of miscommunication of water-related energy in California, The United States, and globally. See Tables 3 and 4 and Supplementary Information 2 for details.

Table 3
Summary of global misunderstandings and miscommuniations of water-related energy (1999–2012).

Reference number in Fig. 3	Reference	Statement	Description of error or outcome	Audience
[1]	Energy Information Administration (2000)	Estimates 1,000 cubic miles (or 4.2 quadrillion litres) of total annual water consumption globally and 381.9 quads total annual world energy consumption.	None, original source.	G,P
[2]	Postel (2001)	Estimates 30% of water is used by urban areas.	None, original source. Better data is available subsequently.	G,P
[3]	James et al. (2002)	"Energy consumed worldwide for delivering water—more than 26 Quads (1 Quad = 10^{15} BTU)— approximately equals the total amount of energy used in Japan and Taiwan combined, on the order of 7 percent of total world consumption."	Misunderstanding implicit in a simplistic calculation using data from [1] and [2] (see SI2 for more information).	G,P
[4]	Hoffman (2004)	"Globally, commercial energy consumed for delivering water is more than 26 Quads, 7% of total world consumption."	Quotes misunderstanding from [3].	G,P
[7]	Addams et al. (2009)	1) "In just 20 years, this report shows, demand for water will be 40% higher than it is today, and more than 50% higher in the most rapidly developing countries."	None, original source; no estimate of energy consumption was found in this report.	G
[10]	World Economic Forum (2011)	1) "A recent McKinsey and Company study found that within two decades, the collective demand of humans for water will exceed foreseen supply by about 40%." 2) "Recent analysis suggests the world could face a 40% shortfall between water demand and available freshwater supply by 2030."	None, secondary source with correct data. Reference cited: [7].	G
[11]	Hoffman (2011)	" … energy is required to lift water from depth in aquifers, pump water through canals and pipes, control water flow and treat wastewater, and desalinate brackish or sea water. Globally, commercial energy consumed for delivering water is more than 26 Quads, 7% of total world consumption."	Quote of misunderstanding. References cited: [4]	G
[12]	UNESCO (2012)	"Out of all energy produced globally, 7%–8% is used to lift groundwater and pump it through pipes, and to treat both groundwater and wastewater (Hoffman, 2011) - a figure that rises to around 40% in developed countries (WEF, 2011)."	Quotes a misunderstanding [4] and misinterpretation [10].	G,P

*Primary Audience (G = Government, P=Public, See Supplementary Information 2 for details).

water (or 4.2×10^{12} m^3) was abstracted at average energy-intensity of 0.6 kWh/m^3 (kilowatt hours per cubic meter) (James et al., 2002), an overly high estimate. Regarding the inordinate "40% in developed countries", we could find no citation in the referenced document (See Table S2-1 in Supplementary Information 2).

Though many authors make exemplary efforts to make sure their results are clearly described and presented (Elías-Maxil et al., 2014; Plappally and Lienhard V, 2012), understanding and communicating the potential role of water in meeting energy and climate change-related priorities is confounded by the widespread misinterpretation of water-related energy.

Water and energy relationships are also widely misquoted and misinterpreted at national scale. Analysis of water-related energy in the U.S. indicated 12.6% of total annual primary energy consumption (13.0 EJ) was used by water users and the water sector (Sanders and Webber, 2012). Total water-related electricity is 16.1% of national annual electricity consumption (611 TWh). Utilities made up approximately 0.5% of the primary energy, and 1.5% of the electricity consumption, respectively. However, media statements attributed the entire quantity to water delivery (see Table S2-1 in Supplementary Information 2). This confusion is echoed in erroneous statements observed by the authors at multiple prestigious international conferences, between 2011 and 2018.

3.3. Miscommunication in California

The challenge of communicating water-related energy has strong historical roots (Table 4). Many publications have drawn on the pioneering and high-quality work published by the California Energy Commission in 2005 (Klein et al., 2005). The work was slightly updated in 2006, however, all water-related energy, including the water users, was attributed to the "water sector" (Navigant Consulting Inc., 2006), even though the 2005 report is clear that the term "water and energy sectors" does not include water users. Careful reading of the 2005 report indicates that "water utilities" consumed 3.0% (7,554 Gigawatt hour (GWh)) of electricity in California in order to treat and pump water to the residential, industrial, and commercial, sectors (Klein et al., 2005). "Wastewater utilities" accounted for an additional 0.8% (2,012 GWh) for pumping and treating wastewater. Utilities supplying water to agriculture used another 1.3% of state electricity (3,188 GWh). Collectively "water and wastewater utilities" used 5.1% of state-wide electricity (Klein et al., 2005), not 20%.

The vast majority of electricity use related to water was shown by the Californian Energy Commission (2005) study to be attributed to water users, e.g. 14.1% (35,300 GWh) of state-wide use (Klein et al., 2005). This included 27,900 GWh of electricity for water use in the residential, commercial and industrial sectors, primarily for water heating or steam production. The 14.1% also included 7,400 GWh electricity for agricultural water use, largely on-farm pumping. Total electricity use by water users, plus water and wastewater utilities, collectively accounted for the (almost) 20% of state-wide electricity.

As an example of recent miscommunication, a 2015 Union of Concerned Scientists (UCS) report claimed: "California's water sector consumes nearly 20% of the state's electricity, and its needs are growing" (Christian-Smith and Wisland, 2015). Many people would not include households or general industry in the "water sector", rather they think largely of "utilities" when this term is used. Though the report goes on to clarify "The water sector uses electricity to pump, treat, transport, deliver, and heat water", the opening claim is misleading because it suggests that utilities themselves use 20% of all electricity in California. In fact, utilities only consume about one quarter of this amount (i.e. approximately 5.1% of state electricity) (Klein et al., 2005). Most water-related electricity use is associated with water end users.

Following this, media coverage in *The Guardian* misquoted the original author and claimed: "California, which uses 20% of its electricity in supplying water, just passed a law to collect emissions data from water utilities" (Loge, 2016). In so-doing, the article attributes the entire use of energy to water utilities. It overlooks the dominant effect of water users (e.g. households), as well as the contribution from wastewater utilities. The body of the 2016 article states the use of energy is in the "water system -from pumping it for delivery to disposing of wastewater", again omitting explicit reference to water end users. Not surprisingly, several U.S. federal and state policy documents have similarly misinterpreted these and related data (Copeland and Carter, 2017; National Conference of State Legislatures, 2014).

3.4. How are miscommunication, misinterpretation and misunderstanding influencing policy?

Miscommunication and attribution of how much and where this energy use occurs through the water cycle makes it difficult to identify significant opportunities in regards to water-related energy efficiency and climate change mitigation programs. For example, the multiple recent misquoted statistics on California's water-related energy and/or electricity use —overemphasising utility - were sparked by California Senate Bill 1425. The Bill encourages utilities to use renewable energy and to better account for, and voluntarily report, their GHG emissions (Chawaga, 2016). This legislation is "a radical departure of how California has been addressing climate change" and, "moves the focus from fossil fuels to water" (Loge, 2016). Progressive as this is, communications about the legislation focus primarily on utilities. In doing so, they miss the larger pool of energy — and associated efficiency opportunities - related to water users. While the Bill does technically enable any large water user to register and report GHG emissions, this has not been the focus.

Several intertwined issues confuse the topic of water-related energy. Drawing on our review, we identify these issues and recommend pathways for consistently addressing them. Table S2-1 (Supplementary Information 2) provides additional detail and examples.

3.4.1. Unclear or inconsistent definitions and inclusions of "water-related energy"

Some authors use "water-related energy" to discuss only utility "energy use", Some include only water users in the residential, industrial, commercial, agricultural sectors. Some address both utilities and users. When end-users are considered, authors may or may not include various sectors such as residential, industrial, commercial or agricultural water users and within each sector different components (or processes) of influence may be included such as heating, cooling, pumping, or on-site treatment (see Fig. 1). Alternatively, studies may focus solely on water heating, typically the large fraction of residential water-related energy (see Table 1) The inconsistent inclusions in the term "water-related energy" mean that studies identify different significant contributors, confounding the discussion. A related issue is that when water heating is included in the definitions together with utilities, it is typically the last item of a long list, describing the components of "water-related energy", implicitly under-emphasising its importance.

3.4.2. Ambiguous, imprecise, or inconsistent use of terms water "sector", "systems", "utilities", and "supply"

While the term "water sector" has generally been used to refer to institutions providing water products or services to consumers, different authors include different groups (e.g. water utilities, wastewater utilities, self-supplied water) within the term. Some articles imply or include water users in "water sector". This has led to confusion as to whether "water-related energy" is attributable to utilities or water users.

The term "water system" has also been used to describe both centralised (i.e utility owned infrastructure) as well as end-user water supplies (such as rainwater tanks, stormwater harvesting schemes, and even appliances). Part of the reason is that the water industry — in the face of the need for improved efficiency and limits to water resources - is undergoing a shift to a "One Water" approach (Paulson et al., 2017). The "One Water" perspective considers all water equally. For example, wastewater can be called "wasted", "used" or "purified recycled" water. This new paradigm means that some authors include wastewater and/or stormwater activities in the boundary of "water systems" whereas others,

Table 4
Examples of water-related energy communication in California (2005–2017).

Reference number in Fig. 3	Reference	Statement	Description of error or outcome	Audience[a]
[5]	Klein et al. (2005)	1) "At the top of this list is California's water-energy relationship: water-related energy use consumes 19% of the state's electricity, 30% of its natural gas, and 88 billion (10^9) gallons of diesel fuel every year – and this demand is growing." 2) "Water supply and treatment account for 22 percent of water-related electricity consumption; 70 percent is required by urban water users and 30 percent by agriculture. On-farm agricultural water use consumes additional energy, estimated at 15 percent of water-related electricity demand. Residential, commercial, and industrial end uses combined represent 58 percent of the electricity consumed. Wastewater treatment accounts for 4 percent. The vast majority of water-related natural gas consumption is by residential, commercial, and industrial customers, primarily for heating water."	None, original source.	G
[6]	Navigant Consulting Inc. (2006)	1) "The WER concluded that the water sector is the largest user of energy in the state, accounting for 19% of all electricity consumed in the state and 30% of non-power plant–related natural gas use[1]." where Note 1 refers to: "Water-related energy included that amount of energy directly consumed by water agencies in the collection, extraction, conveyance, treatment, and distribution of water to end users, and the treatment and disposal of wastewater. In addition, the WER included the amount of energy used to consume water, e.g., to heat water for a shower or to pump it through a cooling tower. Energy consumed during the consumption of water consists primarily of pumping and water heating."	Miscommunication related to definition of "water sector". Ie rather than using definitions of "residential sector, commercial sector" relating to end users of water, (as used by [5]) this report groups them all into the "water sector".	G
[8]	Yudelson (2010)	"In California, water supply and wastewater treatment accounted for 19% of state-wide electricity and 32% of all natural gas use."	Misinterpretation	P
[17]	Murkowski (2014)	"The most energy-intensive activities are the transport, conveyance, and desalination of water. These all require large quantities of energy for pumping water … An obvious solution is to minimise the embedded energy in water conveyance and treatment processes …".	Misinterpretation	G
[22]	Christian-Smith and Wisland (2015)	"California's water sector consumes nearly 20% of the state's electricity, and its needs are growing. The water sector uses electricity to pump, treat, transport, deliver and heat water."	Miscommunication about meaning of "water sector" ie including water end users in the definition of "sector".	G,P
[23]	Pavley (2016)	"This bill would require the [California Environmental Protection Agency] to oversee the development of a registry for greenhouse gas emissions resulting from the water-energy nexus using the best available data."	Legislative outcome	G
[24]	Union of Concerned Scientists (2016)	"The California water sector, primarily water utilities and wastewater treatment facilities, uses nearly 20% of the state's electricity supply, a number that is expected to grow as the ongoing drought further stresses water supplies and the electricity grid."	Misinterpretation	G,P
[25]	Loge (2016)	1) "California, which uses 20% of its electricity in supplying water, just passed a law to collect emissions data from water utilities". 2) "Yet in California, 20% of the state's electricity and 30% of the natural gas that isn't used by power plants goes to the water system – from pumping it for delivery to disposing of wastewater."	Misinterpretation	P
[26]	Jerome (2016)	"A new California law encourages water utilities to collect emissions data as part of an effort to bring more transparency to the enormous amount of power gobbled up by water systems, which use 20% of the state's electricity and 30% of its natural gas."	Misinterpretation	P
[27]	Copeland and Carter (2017)	"In California, for example, as much as 19% of the state's electricity consumption is for pumping, treating, collecting, and discharging water and wastewater."	Misinterpretation	G
[28]	Association of California Water Agencies (Undated)	"Water operations are a major user of energy in California. In fact, pumping, treating and delivering water accounts for about 20% of all electricity used in the state."	Misinterpretation	G,P

[a] Primary Audience (G = Government, P=Public).

taking a more traditional approach, do not. When referred to as "urban water systems", the term generally includes water, wastewater, and stormwater infrastructure and institutions.

Definitions of "water utilities" can depend on the local structure of the institutions involved. Often the term "urban water utility" covers water, wastewater, and stormwater service providers.

3.4.3. Failing to distinguish between primary and secondary energy sources such as electricity

There is wide general confusion caused by poor differentiation of "energy", "primary energy" and other particular forms of energy such as "electricity". When a primary energy source (e.g., natural gas, oil, solar) is converted to secondary energy (e.g., electricity), losses occur. For example, generating electricity in a thermal power plant (coal or nuclear) loses 55–75% of the energy as waste heat (U.S. Energy Information Administration, 2018). Combined heat and power plants are marginally more efficient. Some studies that do consider conversion losses do not specify that they are reporting primary energy in their manuscript (e.g., Zhou et al. (2013) refer to the more ambiguous "total energy"). Some authors consider multiple forms of energy (e.g. electricity, gas and diesel) but convert them all to a single unit without accounting for conversion losses, rendering the comparison less informative. Some authors also interchangeably and imprecisely use the general terms "energy" and "electricity". Conversely, some authors only evaluate a single energy source such as "electricity" and refer to it as energy use, confounding the terms "electricity" and "energy". The implication of an "energy" study is that all forms of energy are included (Kenway et al., 2015). Similarly, some studies that consider forms of energy beyond electricity may not include all potential sources (e.g., natural gas, diesel) (Klein et al., 2005).

3.4.4. Use of non-standard units

A related issue is the wide use of diverse energy units and their expression per unit of water volume, compounding the difficulty in comparison and general confusion. Articles reviewed used diverse energy and water units (kilowatt-hours, therms, BTU (British Thermal Units), quads (quadrillion BTU), tonnes-of-oil equivalents, Joules, gigalitres, MGD (million gallons per day), cubic miles, acre-feet and their combinations (e.g. kWh/m^3, BTU/MGD) (See Appendix A). These diverse unit nomenclatures, coupled with international inconsistency in the use of the term "quadrillion" (ie either 10^{24} in the UK and Europe or 10^{15} in the USA), contribute to substantial confusion when comparing across studies.

Statistics of water-related energy may also mix units of time, for example, reporting energy flows as quads/year while reporting water flows as cubic meters per day. Studies also often rely on single year of analysis to generalise an entire system which can be inadequate in systems with high volatility, for example during drought, without addressing the associated uncertainty (Kenway et al., 2015; Sanders and Webber, 2012).

3.5. Recommendations for a global protocol for water-related energy

A more standardised conceptualisation is needed for quantifying and communicating water-related energy. This is important because the effect is large influencing between 3 and 14% of global primary energy. It is also important because managing water-related energy is pivotal as an effect on greenhouse gas emissions and economies as a direct cost. Finally, it is important because, the current lack of clarity is leading to frequent miscommunication at multiple levels, and its distortion into policy.

Based on our analysis and harmonising multiple studies (and data) in the literature, we advocate for a global water-related energy protocol. This would comprise a consistent set of (1) definitions, (2) methods and (3) metrics for quantifying water-related energy similar to existing method-sets such as the Global Greenhouse Gas Protocol (WRI and WBCSD, 2017). While clarification of all elements of a protocol is beyond the scope of this article, we outline our view of key elements and needs:

1. Clear definition of the institutions, actors, infrastructure, services, processes and activities included in "water-related energy". "Water-related energy" used without clarification should include energy for heating, pressurising, cooling or pumping water by all water end users (including residential, industrial, commercial and agricultural water use), as well as pumping and treatment of water by utilities. Author-defined boundaries should be explicitly stated. We have provided recommended definitions in Section 2.1 of this article. This includes definitions of "water sector", and "water system". Our interpretation is also presented in Fig. 4. We recommend —the term "water utilities" should refer to institutions that provide water, wastewater, and/or stormwater services.
2. All forms of energy (eg electricity, natural gas, diesel etc) should be converted to primary energy consumption including accounting for transmission and conversion losses. By converting to primary energy including losses, it becomes possible to compare water-related energy in different forms of energy use (e.g. solar powered electricity, coal-fired electricity, gas, and diesel). When reporting individual forms of energy use (i.e., electricity, natural gas, diesel, etc.), the forms of energy included, and the conversion and losses accounted for, should be explicitly described. If electricity alone is evaluated, the study and its results should consistently refer only to electricity and not to "energy" use.
3. System International units should be used, since all countries except three have adopted the SI system as their official system of weights and measures. More specifically, we recommend that energy results in Joules (J) should be used for reporting primary energy. Watt hours (Wh) should be used when only electrical energy is evaluated. Water volumes should be reported in cubic meters (m^3) or Litres (L). Whenever necessary, a scientific prefix such as "k" (kilo, 10^3), "M" (Mega, 10^6), "G" (Giga, 10^9), "T" (Tera, 10^{12}), "P" (Peta, 10^{15}), or "E" (Exa, 10^{18}) should be used. Within a paper, use of a consistent time scale (hourly, daily, or annually), helps with interpretation. While this recommendation would appear self-evident, there appears to be no common standard practice in the analysis and communication of water-related energy.
4. Clearer quantitative methods are needed to guide inclusions, exclusions and approach to quantification of water-related energy. It is also needed to guide (where possible) validation. Such a "method set" (similar to method used in the global greenhouse gas protocol (WRI and WBCSD, 2017)) would improve the ability to compare specific components of water-related energy. Development of a complete "method set" for all aspects of water-related energy would be a significant endeavour. Substantial additional work is required to develop detailed agreed methods within each sector of "water-related energy", particularly for residential, commercial, industrial (including mining), and agricultural water-related energy.
5. When components of water-related energy are listed, they should be listed in order from largest contributions to smallest. In the urban water cycle, this would mean that water-related energy of end-users (e.g. in the residential and industrial sectors) would be typically listed before utility energy use.

A protocol, if implemented, would inform a more widely

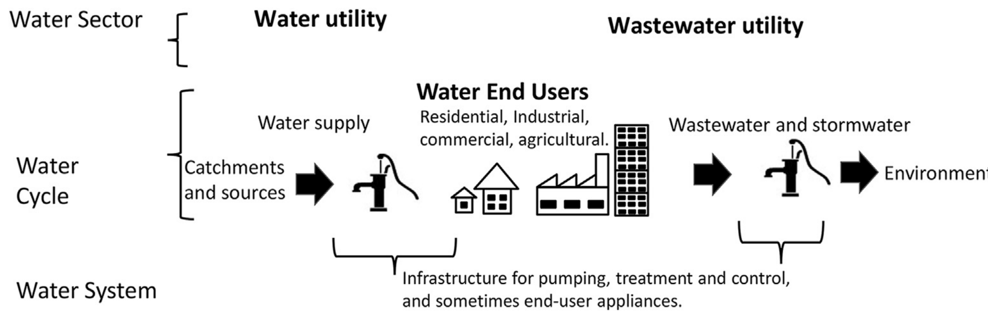

Fig. 4. Illustration of the concepts of “water sector”, “water cycle” and “water system”.

accepted method and definition set and improve the consistency and comparability of results, enabling improved future benchmarking. We note that considerable work is required to develop detailed methods for consistent quantification of water-related energy particularly for residential, commercial, industrial, agricultural and mining water-related energy.

3.6. How will clearer assessment and communication of water-related energy shift discussion?

Managing “water-related energy” and related greenhouse gas emissions is a major challenge, even with clear analysis and communication. Current miscommunication may disproportionately focus attention on energy used by utilities for pumping and treatment, when focussing on water users could be more effective. Water-related energy performance can be improved with water efficiency in homes and industries and by shifting household water-heating to renewable energy supplies such as solar energy, both solar PV and solar heating (Fidar et al., 2010; Gleick, 2003; Thiede et al., 2016). Significant waste heat is lost down the drain as warm water (Elías-Maxil et al., 2014; Larsen et al., 2015; McCarty et al., 2011). Heat recovery from bathrooms (e.g., shower drain coils) (Meggers and Leibundgut, 2011), homes (e.g., heat pumps), sewers and at wastewater treatment plants has potential to “recycle” energy, e.g., for water or building heating (Kollmann et al., 2017; Larsen, 2015; McCarty et al., 2011). Small-scale implementations can be more cost-effective than utility-scale options (Lam et al., 2017), and is expected to be more prevalent in future (Knoeri et al., 2016).

There are currently no, or at best marginal, financial benefits for water (or energy) utilities to help water users become more efficient despite large potential cost savings. Some energy policies are already in place for water-related end-use technologies. For example, around 25 countries and the European Union have energy- or water-efficiency standards or labels for water heaters and clothes washers (CLASP, 2017). Many jurisdictions have efficiency standards for water use for toilets, faucets, showerheads and urinals. However, the presence and benefits of such programs are often masked in the discussion around the water-energy nexus by the more prominent, often incorrect, statistics relating to water utilities.

At a larger-scale, district heating systems are providing cost-effective solutions and replacing individual household hot water systems. District heating captures waste heat from power stations or incinerated solid waste to deliver hot water into homes and industries. These systems have been instrumental in a range of countries meeting their greenhouse gas emissions targets (Rezaie and Rosen, 2012).

Having better data is never enough to change minds, much less policy (see literature critiquing the knowledge deficit model of science communication, e.g. (Simis et al., 2016)). The ‘science-to-policy’ literature abounds with frustration concerning the difficulties of translating improved results into better policy and regulation (Head, 2016). For policies to be effective, clear messages using accessible language, targeted toward key stakeholders and decision-makers (e.g., utilities, consumers and politicians) are needed (National Academies of Sciences, 2016).

If research and management on the water-energy nexus is to move the climate change focus “from fossil fuels to water” (Loge, 2016) the discussion on water-related energy needs to include not only utilities but also water users. We argue that this wider, more holistic perspective is required for cost-effective investment. The current quantification and communication problems are hindrances to the identification and prioritisation of investments in efficiency improvement.

Water-related energy is one component of the wider “water-energy-land” or “water-energy-food (or climate)” nexus (Khan et al., 2017), a multi-faceted issue spanning all links in production, supply and consumption of water, energy, food and fibre. For example, a connection exists between food production, water use and energy consumption: if food production patterns shift, so too does water and energy use. The broader “nexus” concept is a multi-disciplinary and multi-sectoral topic of major international significance. A nexus perspective has been argued as essential for “effective implementation of the Sustainable Development Goals” (Pahl-Wostl, 2019). Unfortunately, this wider “water-energy-food” nexus is also prone to confusion stemming from poorly-defined terms and concepts. By improving definition, and quantification of the better defined water-energy nexus component, we also advance this wider nexus perspective.

3.7. Implications for theory and practice in sustainable cleaner production

This work has considerable implications for assessment and management of sustainability in cleaner production. Contributions to theory can be considered with regard to: “What is included?” (factors and variables), “How?” (inter-relationships between the factors), and “Why?” (credibility and logic of inclusions and interrelations), see Whetten (1989). The framework developed here is helpful to interpret conceptual and practical implications for future (i) quantification of water-related energy and (ii) communication and formulation of policies regarding water-related energy.

This paper systematically establishes “What” elements of water-related energy have been included in widely inconsistent interpretation and methods. Inclusions range from a narrow “utility” perspective through progressive incorporation of water use in residential, industrial, commercial and agricultural activities. The understanding of “How” water and energy are interrelated is also improved by articulating the cause-and-effect relationship, and by much more clearly attributing water end users as a major source of the interconnection. For both “What” and “How” water-related energy is determined within each domain (utilities and water end users), further development is needed to improve comparability.

Finally, “Why?” should credence be taken of our perspective? One reason for supporting more consistent interpretation of water-related energy is that it would make comparisons much more readily done without the need to calculate and recalculate numbers using different boundaries and interpretations of vaguely described inclusions or exclusions. This clarity, together with stronger empirical justification, will have significant repercussions for related methods including Life Cycle Assessment, and global protocols for greenhouse gas reporting (particularly Scope 3 emissions), for example. For sustainable production, our work raises the question of whether industry should focus on either (a) its own domain of operation and/or (b) on the efficient use of its products. It would be timely to adopt a clearer framework for quantifying water-related energy given the rapid growth of studies in this area in response to the clear need for improved global, national and regional analysis.

Clearer conceptualisation of “water-related energy” has implications for accounting of the energy (and greenhouse gas impact) for water, and related monitoring. A global protocol for water-related energy will influence strategies and measures for which water utilities could validly demonstrate impact on energy and greenhouse gas emissions (e.g. by supporting water end users to reduce water use and consequently energy and related emissions). This paper (and a protocol) would enable much stronger discussion on the relative merit of the water sector reducing its own operational energy use (e.g., more efficient pumping, treatment unit process selection), or whether it is more strategic to reduce the energy effect of water by focussing more on water use. The Global Reporting Initiative for government encourages this by reporting on the impact of their policies, not just their operations (Global Reporting Initiative, 2005).

Reflecting on the value of theory in management Suddaby (2014) notes “Effective science is the result of a collective and institutionalized commitment to a system of knowledge production that is organized around keeping each of individual biases and value propositions in check.” If this paper leads to a more consistent global system of knowledge regarding water-related energy water, it will be a big step forward for management of the wider water-energy nexus.

3.8. Limitations and future research needs

We highlight throughout this article challenges of definitions, inclusions/boundaries, transformations, language and many other factors. While this work has hopefully improved clarity of the overall issue, much further work into detailed methodologies for quantification of water-related energy is required. For example, while the direct energy use of water utilities (e.g. electricity or diesel used) is relatively well known, very little is understood of the energy effect that delivery of water at different temperatures could impact on end users. More widely quantification of water-related energy of residential, industrial and commercial water users is a relatively new field, and in great need of methods to address widely differing situations of water use, technologies, behaviours etc. Similar to the global effort to develop a global GHG protocol, much improved methods are required for more systematic analysis of water-related energy.

To our knowledge, this is the first study which has sought to define, and track communications regarding water-related energy. Further research could sharpen such analysis, potentially drawing on this article as a benchmark.

4. Conclusions

Our objectives were to (i) develop a more consistent framework for conceptualising and assessing “water-related energy”, (ii) apply this to existing studies and datasets to enable comparisons, and (iii) track how the issue has been communicated.

Using the developed framework and definitions to answer “How is miscommunication of water-related energy influencing policy?” we show significant confusion communicating water-related energy. This is at least partially due to (i) inconsistent inclusions (ii) unclear terms such as water “system”, “sector”, and “supply”, (iii) frequent failures to distinguish primary energy and electricity, and (iv) wide use of non-standard units. Collectively, these factors make comparing studies extremely difficult. Not surprisingly, frequent miscommunication results including translation into policy. In answering how significant is water-related energy? we identify challenges analysing and comparing across international literature. Various studies and datasets, when analysed consistently, demonstrate that water users, and water utilities collectively influence 2.6–12.6% of regional total regional primary energy consumption. Residential, industrial and commercial water use accounts for most water-related energy, primarily for water heating. Water and wastewater utilities use 0.4–2.3% of primary energy or 0.6–6.2% of regional electricity. This is substantial, but far lower than claims made in many important policy documents.

Finally, we put forward a set of recommendations, based on this harmonisation effort, aiming to establish how will clearer assessment and communication of water-related energy will shift discussion? We argue this clarity is necessary to improve the consistency, accuracy, comparability and value of water-related energy analysis. The framework and definitions developed in the article are suggested as a starting point and a step towards formulation of a full protocol and method.

Clearer conceptualisation of water-related energy will not singlehandedly solve the problem of miscommunication and its influence on policy and investment. However, greater consistency of analysis will certainly help reveal, and guide more policy attention towards, the significant impact of water end use.

Acknowledgements

The authors thank Arpad Horvath, Paul Lant, and Paul Dargusch for review of earlier drafts of this paper. Steven Kenway acknowledges the Australian Research Council through a Discovery Early Career Researcher Award (DE100101322). Ka Leung Lam acknowledges funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 707404. Jennifer Stokes-Draut acknowledges funding provided by the National Science Foundation-funded Reinventing the Nation’s Urban Water Infrastructure (ReNUWIt) Engineering Research Center (http://renuwit.org; NSF grant no. CBET-0853512).

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.06.333.

Appendix A. Units

BTU: British Thermal Unit is the unit of energy needed to cool or heat one pound of water by 1° Fahrenheit.

EJ: Exajoule 1,000,000,000,000,000,000 or 10^{18} J

GL: Gigalitres (1,000,000,000 L or 10^9 L)
GWh: Gigawatt hour (10^6 kWh or 10^9 Wh)
Joule: Joule (1 W second)
kWh: kilowatt hour (1000 Wh)
m: Metres
MGD: Million Gallons per Day
ML: Megalitre (1,000,000 L or 10^6 L or 1,000 m^3)
PJ: Petajoule 1,000,000,000,000,000 or 10^{15} J
Quads: Quadrillion BTU's (1 Quad = 10^{15} BTU). Note that quadrillion in Europe means 10^{24} and in the US it means 10^{15}.
TJ: Terajoule 1,000,000,000,000 or 10^{12} J
TL: Teralitre (1,000,000,000,000 L or 10^{12} L)

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